

**ENSEMBLE RE-FORECASTING :  
IMPROVING MEDIUM-RANGE FORECAST SKILL  
USING RETROSPECTIVE FORECASTS**

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## ABSTRACT

The value of the Model Output Statistics (MOS) approach to improving 6-10 day and week 2 probabilistic forecasts of surface temperature and precipitation is demonstrated. Retrospective two-week ensemble “re-forecasts” were computed using a reduced-resolution T62L28 version of the NCEP medium-range forecast model with physics operational during 1998. NCEP-NCAR reanalysis initial conditions and bred modes were used to initialize the 15-member ensemble. Probabilistic forecasts of precipitation and temperature were generated using a logistic regression technique with the ensemble mean (precipitation) or ensemble mean anomaly (temperature) as the only predictor. Forecasts were computed and evaluated during 23 winter seasons from 1979 to 2001.

Evaluated over the 23 winters, these MOS-based probabilistic forecasts were skillful and highly reliable. When compared against operational NCEP forecasts for a subset of 100 days from the 2001-2002 winters, the MOS-based forecasts were comparatively much more skillful and reliable. For example, the MOS-based week 2 forecasts were more skillful than operational 6-10 day forecasts. Most of the benefit of the MOS approach could be achieved with 10 years of training data, and since sequential sample days provided correlated training data, the costs of re-forecasts could also be reduced by skipping days between forecast samples.

MOS approaches will still require a large data set of retrospective forecasts in order to achieve their full benefit. This forecast model must remain unchanged until re-forecasts have been computed for the next model version, a penalty which will slow down the implementation of model updates. Given the substantial improvements noted here, it is argued that re-forecast based MOS techniques should become an integral part of the medium-range forecast process despite this cost. Techniques for computing re-forecasts while minimizing the impact to operational weather prediction facilities and model development are discussed.

## 1. INTRODUCTION

Improving weather forecasts is a primary goal of the U.S. National Oceanic and Atmospheric Administration (NOAA) and other weather services. One commonly emphasized way to improve weather predictions has been to improve the accuracy of the numerical forecast models. Much effort has been expended to improve the estimate of the initial condition (e.g., Daley 1991, Parrish and Derber 1992, Courtier et al. 1994, Houtekamer and Mitchell 2001), to conduct forecasts with higher-resolution numerical models (e.g., Weisman et al. 1997, Kalnay et al. 1998, Buizza et al. 2003), and to incorporate more complex physical parameterizations of processes that occur below the grid scale. Within the last decade, ensemble forecast techniques (e.g., Toth and Kalnay 1993, 1997, Molteni et al. 1996, Houtekamer et al. 1996) have also been embraced as a tool for making probabilistic forecasts and for filtering the predictable from the unpredictable scales (via ensemble averaging).

There are forecast situations that are so intrinsically difficult that skill has not improved much despite the investment in large new computers and despite the millions of person hours invested in model development over the last 40 years. Medium-range weather forecasting is one such endeavor. The skill of these forecasts is marginal because of the inevitable rapid growth of errors through chaos (e.g., Lorenz 1969) and because of the steadier growth of model errors. In order to make a skillful medium-range forecast, forecasters must thus be able to adjust for model systematic errors and be able to distinguish between features that are predictable and those that are unpredictable. As will be shown later, unprocessed numerical guidance is often not particularly useful; for example, probability forecasts that are derived from the National Centers for Environmental Prediction (NCEP) ensemble forecasts' relative frequency have no skill and are highly unreliable.

The format of forecasts issued by the NCEP Climate Prediction Center (CPC) implicitly reflect a judgment of what can be predicted skillfully and what cannot. Daily details of synoptic-scale features are considered largely unpredictable, while shifts in the probability density function of averages over several days may be predictable. Consequently, CPC produces probability

forecasts of time averages of the deviations from climatology. Specifically, CPC makes 6-10 day and week 2 (8-14 day) forecasts of surface temperature and precipitation tercile probabilities. These are forecasts of the probability that the temperature and precipitation averaged over these periods will be below the 33rd or above the 67th percentile of the distribution of climatological observed temperatures and precipitation. Forecasters at CPC synthesize information from the NCEP ensemble prediction system as well as models from other weather services and other statistical tools. As will be shown, the skill of operational week 2 forecasts is currently quite low.

Another possible way of improving weather forecasts is to adjust the forecast model output using a database of retrospective forecasts from the same model. The adjustment of dynamically based forecasts with statistical models has a rich history. Model Output Statistics, or “MOS” techniques (Woodcock 1984, Glahn, 1985, Tapp et al. 1986, Carter et al. 1989, Vislocky and Fritsch 1995, 1997) have been used widely since the 1970s. However, in recent years, the U.S. National Weather Service (NWS) has de-emphasized the use of MOS techniques using fixed models; such an approach requires a large sample of forecasts from the same model to achieve their maximal benefit. This implies that a large number of retrospective forecasts must be run prior to implementation of a new model version and that the current forecast model be “frozen” until retrospective forecasts are computed for any planned new model version; changing the model numerics may change the forecasts’ error characteristics, invalidating the regression equations developed with the prior model version. Consequently, decision makers at many weather prediction facilities have judged that forecast improvements will come much more rapidly if the model development is not slowed by the constraints of computing these retrospective forecasts.

Statistical algorithms like MOS improve on raw numerical forecasts by implicitly removing model bias and filtering the predictable from the unpredictable. Given the difficulty of doing this without statistical models, and given the marginal skill of current week 2 weather forecasts, we reconsider the value of statistical weather forecasting for this application. Specifically, we will examine here whether a reduced-resolution ensemble prediction system calibrated using a set of prior numerical forecasts can produce forecasts that are more skillful than the products

generated by human forecasters based on a variety of state-of-the-art, higher-resolution models. A reduced-resolution (T62) version of NCEP's Medium-Range Forecast (MRF) modeling system using 1998 model physics was used to run a set of ensemble re-forecasts over the period 1979-2001. Statistically adjusting current T62 forecasts using these prior forecasts will be shown to produce substantial improvements in forecast skill, greatly exceeding the skill of the operational forecasts. We will document the skill of these forecasts and examine how many retrospective forecasts are necessary to approach optimum skill. Given the improvements produced through the use of statistical techniques, we propose that "re-forecasting" and the application of MOS-like statistical techniques should become an integral part of the medium-range numerical weather prediction process.

Below, Section 2 will outline the forecast modeling system and provide details on the general statistical approaches used. Section 3 presents results, and Section 4 concludes with a discussion of the implications of this research.

## 2. EXPERIMENT DESIGN

### *a. Forecast model, initial conditions, and verification data*

A T62 resolution version of NCEP's MRF model (Kanamitsu 1989, Kanamitsu et al. 1991, Caplan et al. 1997) was used to generate an ensemble of 15-day forecasts over a 23-year period from 1979 to 2001. Further details regarding the model formulation can be found in Newman et al (2003). A 15-member ensemble was produced every day of the 23 years using 0000 UTC initial conditions. The ensemble consisted of a control forecast initialized from the NCEP-National Centers for Atmospheric Research (NCAR) reanalyses (Kalnay et al. 1996) and a set of 7 bred pairs of initial conditions (Toth and Kalnay 1993, 1997) re-centered each day on the reanalysis initial condition.

Forecasts were evaluated in two ways. First, the new MOS-based forecasts were evaluated over winter seasons (December-February) in a 23-year period from 1979 to 2001. A set of 355 stations in the U.S., Guam, and the Virgin Islands were used for this comparison. The large ma-

jority of these stations are in the conterminous U.S. (all dots in Fig. 1). These 355 stations were chosen as the subset of available cooperative network (co-op) stations with at least a 90 % complete record (Eischeid et al. 2000) from 1979 to 2001. Second, the MOS-based forecasts were compared against NCEP Climate Prediction Center (CPC) operational forecasts for a set of 100 days during the winters of 2001 and 2002. This comparison was performed at the subset of 153 stations where CPC forecasts were available (darkened dots in Fig. 1). The observed climatology used in these experiments was determined from 1971-2000 data, consistent with CPC practice.

*b. Logistic regression model and forecast / evaluation process*

Following the format of operational 6-10 day and week 2 forecasts produced at CPC, we produced forecasts of the probability distribution of precipitation and surface temperature at the stations. Probabilities were set for three categories, the lower, middle, and upper tercile of the distribution of observed anomalies from the mean climatological state. The method for determining the upper and lower tercile anomaly boundaries ( $T_{2/3}$  and  $T_{1/3}$ , respectively) is discussed below.

A logistic regression technique (e.g., Wilks 1995, Applequist et al. 2002) was used for this experiment; the interpolated ensemble-mean forecast or forecast anomaly as the only predictor. Separate regression analyses were performed for each observation location. By regressing on the ensemble mean rather than a single forecast, we exploited the ability of ensemble averaging to filter out the smaller, unpredictable scales and retain the larger, predictable ones.

The logistic regression model sets the probability that the observed anomaly  $V$  will exceed  $T_{2/3}$  or  $T_{1/3}$  according to the equation (here, for the upper tercile)

$$P(V > T_{2/3}) = 1 - \frac{1}{1 + \exp(\hat{\beta}_0 + \hat{\beta}_1 x)} \quad (1)$$

where  $x$  is the ensemble mean forecast anomaly and  $\hat{\beta}_0$  and  $\hat{\beta}_1$  are fitted regression coefficients.

We tested other possible predictors to use in the logistic regression analysis. A regression analysis using only the control forecast rather than the ensemble mean provided less skill, as dis-

cussed later. A regression analysis in the basis of the leading canonical correlates (Wilks 1995) was less skillful than one using just the ensemble mean. Similarly, some obvious candidates such as ensemble spread did not improve forecast accuracy. Figure 2 illustrates why spread was not a useful predictor; correlations of ensemble-mean error and spread were uniformly low, never exceeding 0.2. It was not clear whether a stronger spread-skill relationship ought to exist at these scales and lead times. It is known that accurate estimates of spread require larger ensembles than accurate estimates of the mean (Compo et al. 2001) and that the current breeding method for generating perturbations is sub-optimal (Hamill et al. 2000, Wang and Bishop 2003), perhaps leading to less of a spread-skill relationship than may be possible.

The process for producing and evaluating MOS forecasts are described here for week 2 forecasts of upper-tercile probabilities. Lower-tercile probabilities and 6-10 day probabilities were handled in an identical manner. The regression parameters were determined using a data set of ensemble mean week 2 anomalies from climatology. From these we compute the associated binary verification data (was the observed anomaly above the upper tercile ( $P(V > T_{2/3} = 1)$  or below or equal to it ( $P(V > T_{2/3} = 0)$ ? Regression coefficients were determined through a cross-validation approach (Wilks 1995) to ensure the independence of the training and evaluation data. For example, given 23 years of available forecasts, when making forecasts for a particular year, the remaining 22 years were used as training data. The same 22 years were used to define the forecast climatology.

The generation and evaluation of tercile probability forecasts followed a 3-step process. The process is described for a week 2 forecast; an identical process was used for the 6-10 day forecasts. The three steps were:

(1) *Train*: (a) Calculate a daily running mean climatology of the week 2 forecast and week 2 observed values individually for each station. The observed climatology used observations from 1971 to 2000; the forecast climatology used forecasts from 1979 to 2001. The year for which the forecast is being made was excluded from both. For a given year and day of the year, the climatology was the week 2 value averaged over all sample years and the 31 days (15 before,

15 after) centered on the date of interest. The process was repeated for each year and day of the year. (b) Determine the forecast and observed anomaly by subtracting the climatology. [Repeat this for each year, day, and station]. (c) Generate a training data set of  $22 \times 31$  samples of week 2 ensemble mean forecast anomalies and week 2 observed anomalies using a 31-day window centered on the day of interest. [Repeat]. (d) Set the observed upper tercile anomaly  $T_{2/3}$  as the 67th percentile of the sorted observed anomaly data. [Repeat]. (d) Create the  $22 \times 31$  binary verification data samples. Each sample verification is categorized as being above the upper tercile ( $P(V > T_{2/3} = 1)$ ) or below or equal to it ( $P(V > T_{2/3} = 0)$ ). [Repeat]. (e) Determine  $\hat{\beta}_0$  and  $\hat{\beta}_1$  through logistic regression using the ensemble mean anomaly as the only predictor<sup>1</sup>. [Repeat].

(2) *Forecast* : Produce tercile probability forecasts for this particular year/day/station in DJF using eq. (1).

(3) *Evaluate* : After forecasts have been produced for each day in DJF for each of the 23 years using this cross-validation process, evaluate the forecast accuracy using the ranked probability skill score (RPSS; Wilks 1995) and reliability diagrams (ibid).

To determine the RPSS, let  $\mathbf{y}_i = [y_{1,i}, y_{2,i}, y_{3,i}]$  represent the probabilities assigned to each of the 3 categories for the  $i$ th forecast of  $n$  samples. Similarly, denote an observation anomaly probability vector for the  $i$ th forecast,  $\mathbf{o}_i = [o_{1,i}, o_{2,i}, o_{3,i}]$ , composed of 0 and 1. For example, if the observed anomaly was lower than  $T_{1/3}$ ,  $\mathbf{o}_i = [1, 0, 0]$ . Define cumulative forecast and observation functions:

$$\mathbf{Y}_i = [Y_{1,i}, Y_{2,i}, Y_{3,i}] = [y_{1,i}, (y_{1,i} + y_{2,i}), (y_{1,i} + y_{2,i} + y_{3,i})] \quad (2)$$

and

$$\mathbf{O}_i = [O_{1,i}, O_{2,i}, O_{3,i}] = [o_{1,i}, (o_{1,i} + o_{2,i}), (o_{1,i} + o_{2,i} + o_{3,i})] \quad (3)$$

<sup>1</sup>We have used both Alan Miller's freely available Fortran90 module logistic.f90 (available from <http://users.bigpond.net.au/amiller/>) and the the Numerical Algorithms Group (NAG) library routine g02gbf to perform logistic regression with nearly identical results.



The ranked probability score of the forecast is then defined as

$$RPS_f = \sum_{i=1}^n \sum_{j=1}^3 (Y_{j,i} - O_{j,i})^2. \quad (4)$$

The RPSS can then be calculated as

$$RPSS = 1. - \frac{RPS_f}{RPS_{clim}} \quad (5)$$

where  $RPS_{clim}$  is calculated assuming the climatological forecast probabilities for the three tercile anomalies are  $[1/3, 1/3, 1/3]$ .

Figure 3 illustrates the process for determining the regression model for 850 hPa temperatures, here for a location along the Oregon coast on Dec 16. A scatterplot of the ensemble mean week 2 forecast anomaly was plotted against the corresponding week 2 observed anomaly using the 22 years  $\times$  31 days of samples. From the observed data, the upper and lower terciles were calculated (horizontal dashed lines). Sample points where  $P(V > T_{2/3}) = 1$  are denoted with red dots and points where  $P(V > T_{2/3}) = 0$  with blue dots. If one were to set the upper tercile probabilities just using the relative frequencies of observed values in a bin around a forecast value (the bin limits denoted by the vertical lines), then the average bin probabilities would be denoted by the horizontal solid lines. For example, counting all the forecasts with an anomaly between -6 and -4 C and tallying how often the observed anomaly exceeds the upper tercile, the probability was approximately 12 percent. When all the samples were supplied to the logistic regression, probabilities were determined as a smooth function of the forecast anomaly according to the dotted curve.

Precipitation forecasts used a slightly modified method. Ensemble mean precipitation forecasts and observed values were used without removing the climatological mean. Also, because precipitation forecast and observation data tends to be non-normally distributed, the precipitation forecasts and observations were power transformed before applying the logistic regression. Specifically, if  $x$  denotes the ensemble mean forecast, we generated a transformed forecast  $\tilde{x}$  according to  $\tilde{x} = x^{0.25}$ , and  $\tilde{x}$  was used as the predictor. The process is illustrated in Fig. 4.

Some stations were so dry that precipitation terciles were impossible to define. For example, in late January in Phoenix, Arizona, approximately  $p = 60$  percent of the week 2 observed samples had no rainfall. Hence, the 33rd percentile of the distribution was zero, but so were the 50th and 60th percentiles. Special rules were needed for such cases. We decided to use the following rule: in the case of more than 33 percent zero samples in the observed climatology, the lower tercile threshold was defined as the smallest non-zero precipitation value. Hence, for the lower tercile, step 1(d) above produces a binary set of observed probabilities analogous to a probability of precipitation, or POP; that is, a 1 was assigned to nonzero precipitation events and a zero was assigned to zero precipitation events. Similarly, when evaluating the skill score relative to climatology at such points, the probabilities assigned to the 3 categories were no longer  $[1/3, 1/3, 1/3]$ , but  $[p, 2/3 - p, 1/3]$ . During DJF, there were no stations where there were more than  $2/3$  of the samples with zeros.

### 3. RESULTS

Before discussing the results using the MOS algorithm, we note in passing that probability forecasts derived from the raw ensemble have essentially no skill. For example, Fig. 5a shows the reliability diagram for 850 hPa temperature forecasts over 23 years as derived from ensemble relative frequency, verified over the Northern Hemisphere north of  $20^\circ$  N latitude. The reliability of tercile forecasts for the upper and lower terciles were different from each other (due to model bias), and the RPSS was near zero. Larger biases made the corresponding surface temperature and precipitation forecasts even worse (not shown). Removing the model bias (by computing forecast anomalies relative to the 23 year model climatology rather than the observed climatology) improves the forecasts somewhat, resulting in a RPSS of 0.09 (Fig. 5b). However, bias correction alone does not improve the reliability of the forecasts. Note that operational CPC forecasts are not based primarily on the raw ensemble probabilities; instead they rely on guidance from a number of ensemble forecast systems and statistical methods.

#### *a. Skill using full re-forecast data set*

How much should we expect the RPSS to improve by using the re-forecast MOS methodology? If we assume that the forecast and observed 850 hPa temperatures have Gaussian statistics, and that the spread of the ensemble does not vary from day to day (an assumption supported by the low spread-error correlations shown in Figure 2), it is possible to relate the temporal correlation between the ensemble mean forecast and the verifying analysis to the expected RPSS of tercile probability forecasts. This is done by creating correlated time series (representing the ensemble mean forecast and the corresponding verification) by drawing two random samples from a bivariate normal distribution having a specified correlation. Since the variance of the forecast and analysis distributions are fixed (and known) the tercile probabilities can be calculated given the ensemble mean forecast value by integrating the cumulative distribution function for a Gaussian. Figure 5c shows the expected RPSS for tercile probability forecasts as a function of correlation calculated in this manner. After removing the forecast bias, the average temporal correlation between the week 2 ensemble mean and analyzed 850 hPa temperature for all Northern Hemisphere grid points in winter is 0.5. From Figure 5b, we would then expect an RPSS after MOS calibration of 0.16. Figure 5d presents the 850 hPa temperature probabilistic forecasts using the re-forecast MOS methodology. These forecasts are significantly more skillful than those produced by raw ensemble counts. Extreme probabilities are issued less frequently, but when they are issued, they are highly reliable. The RPSS agrees almost exactly with what was predicted by the simple statistical model, suggesting the potential for improvement has been realized. Further improvements in RPSS are not likely without increasing the correlation between the ensemble mean forecast and the analysis.

Hereafter, we will focus on the evaluation of surface temperature and precipitation forecasts. Figures 6 a-b and 7 a-b present reliability diagrams for 6-10 day and week 2 MOS forecasts, respectively. The forecasts were highly reliable and somewhat skillful. There was more skill in temperature than precipitation and substantially more skill for 6-10 day forecasts than for week 2 forecasts. Forecasts regressed on the ensemble mean were somewhat more skillful than those regressed on the control (6-10 day RPSSs were 0.24 and 0.06 for temperature and precipita-

tion using the control, and 0.11 and 0.02 for week 2 forecasts, respectively). The forecasts were sharper (i.e., extreme probabilities issued more frequently) for 6-10 day forecasts than for week 2 forecasts; this was to be expected, for the longer-lead forecasts should more closely resemble the climatological distribution of  $[1/3, 1/3, 1/3]$  always being issued. Surface temperature forecasts were sharper than precipitation forecasts. Generally, many prior studies have found that precipitation is one of the most difficult elements to predict. These results reinforce this general conclusion.

The geographic variations in forecast skill are illustrated in Figs. 8 and 9. Surface temperature forecasts were most skillful in the eastern U.S. and the Ohio Valley. Precipitation forecasts were most skillful along the west coast.

*b. Comparison against operational NCEP forecasts*

The skill of temperature and precipitation forecasts in Figs. 6-7 may seem unimpressive at first glance. However, most prior studies have shown marginal or nonexistent skill for these longer-lead forecasts. For example, Eckel and Walters (1998) showed that even after recalibration with a short training data set, daily precipitation forecasts based on the MRF had negative skill beyond day 6. Hence, did CDC's re-forecast based MOS forecasts improve upon the presumed state of the art, operational NCEP/CPC forecasts? We compared the two using a set of 100 days of DJF data from 2001-2002 at the subset of 153 stations shown in Fig. 1 (darkened dots). Data prior to the year 2000 were used to train the CDC re-forecast MOS algorithm.

Figures 10 and 11 show reliability diagrams and RPSSs for the CDC re-forecast and operational CPC 6-10 day forecasts, respectively. Figures 12 and 13 provide the week 2 forecast diagrams. With a smaller sample size, the CDC re-forecasts were less reliable than they were when validated over all 23 years, as was to be expected (Wilks 1995, Fig. 7.9f). However, the re-forecasts were significantly sharper and more reliable than the operational CPC forecasts and hence much more skillful. In fact, the CDC re-forecasts were more skillful at week 2 than the CPC forecasts were at 6-10 days. Equivalently, this indicates that over these two winters, *the application of the MOS approach increased the effective forecast lead time by several days.*

### *c. Skill with smaller training samples*

The less computationally demanding it is to compute these re-forecasts, the more likely the operational centers are to adopt these techniques. We thus examined how much less forecast skill will result when less than the full 22 years of training data are used. We found that the logistic regression scheme occasionally was unable to generate forecasts with only one or sometimes two years of data; more was needed for computational stability. Figure 14 plots the RPSS of the forecasts for training samples of various sizes. Most of the usable skill has been obtained once  $\sim 10$  years of training data is available. Most likely, another decade of re-forecasts are not worth the extra computational burden.

Another possibility is that if, say, computational considerations prohibit more than 4 years of re-forecasts, these re-forecasts could span anywhere from 4 to 19 years of meteorological conditions by skipping 1 to 5 days between cases (though the control run and breeding cycle would need to be run every day). Figure 15 illustrates that indeed, if there is a fixed upper limit to the number of re-forecasts that could be computed, MOS based on a sample of re-forecasts that were comprised of a training data set with more days between samples was more skillful than those based on a set with fewer days between samples. For surface temperature, given 5 days between samples, four years worth of training data produced probabilistic forecasts that were almost as skillful as those obtained with the full 22-year training data. For precipitation, forecasts were more skillful with increasing time between samples, but the skill of four years of training data, even with 5 days between samples, was still less than that achieved with the full 22 years of training data. The 1-day lagged autocorrelation of precipitation error was 0.75, compared to a temperature autocorrelation of 0.85. Hence, precipitation forecasts probably had more effective degrees of freedom than temperature forecasts and thus benefited more from larger training data sets for the regression analysis.

## 4. DISCUSSION AND CONCLUSIONS

Improving forecasts through the use of MOS techniques applied to fixed models has been de-emphasized during the past decade. These techniques require that a large sample of forecasts and associated verification data be available for the regression analysis. This additional computational burden could potentially slow down the implementation of model changes. In this article, however, we demonstrated dramatic improvements in medium- to extended-range forecasts are possible using MOS techniques. Using a low-resolution model and 22 years of training data, it was possible to make probabilistic week 2 forecasts that were more skillful than the current 6-10 day operational forecasts during the 2001-2002 winters. This improvement occurred despite the fact that operational forecasts are based on larger ensembles and higher-resolution models - but without knowledge of their biases and error statistics.

Can the computational expense of these re-forecasts be reduced? Probably yes. Most of the skill improvement was retained with only 10 years of data. Also, if the training process were constrained to, say, computing only 4 years of re-forecasts, it was preferable to compute re-forecasts over a 19-year span, skipping 5 days between samples. In this way, a broader diversity of weather scenarios were sampled. Computational expense may also be reduced by using a smaller ensemble. We have shown that the skill of 6-10 day MOS forecasts of surface temperature using only the control run are comparable to those obtained using the 15-member ensemble mean (although the differences for precipitation and week 2 forecasts are larger). This is consistent with the notion that the benefit of ensemble averaging is a function of the ratio of the predictable signal (i.e. the ensemble mean anomaly) to the unpredictable noise (i.e. the ensemble spread). Ensemble averaging produces the largest relative increase in anomaly correlation skill when this ratio is small, and the benefit of adding more ensemble members decreases as this ratio increases (cf. Figure 15 in Compo et al 2001). Although we have not investigated the impact of ensemble size here, it is possible that most, if not all, of the skill of the MOS forecasts could be recovered with a significantly smaller ensemble.

Are there other ways of minimizing the impact on operations and model development? Re-forecasts are easily parallelizable, and the ideal re-forecast computing system need not com-

pete for time on the production computer system. As long as ensemble initial conditions have been pre-computed, then many days of re-forecasts can be computed simultaneously on computers or CPUs separate from the production system. For this experiment, our hardware consisted of 72 CPUs. Each compute node consisted of a 2.2 GHz Pentium processor with a 20 GB hard drive and 1 GB RAM. The individual CPUs were not connected with any special hardware to speed message passing. This equipment, including 2.5 TB of extra storage, cost in total about \$ 90,000 US in 2002 dollars. It took approximately 10 months to compute the full 23 years of re-forecasts at T62L28 resolution on this equipment. While operational centers may prefer to compute such re-forecasts with higher-resolution models, by thinning the re-forecasts as previously discussed, it is likely that computer clusters on order of several hundreds of thousands of dollars may be suitable for generating these re-forecasts. The re-forecasting tax thus consists of the up-front cost of hardware and a small staff to maintain the hardware and to run the forecasts and develop the regression algorithms. The more often the operational forecast model is changed, the more expensive the re-forecast effort becomes, since the re-forecasts must then be completed more rapidly.

If the freedom to continually update the model is deemed extraordinarily important, another possible compromise is for operational facilities to run two model versions. One model version would be continuously updated, as is done currently. A second version would be the dedicated “re-forecast” run. This model would operate unchanged until a full data set of re-forecasts are available for the next model version.

It is possible that some model changes may further improve the MOS-based forecasts. For example, the MOS approach may be worth re-testing with higher-resolution ensemble forecasts (Buizza et al. 2003) and improved ensemble perturbation methods that produce larger spread-skill relationships (e.g., Wang and Bishop 2003).

Though this article has focused on the direct benefit of MOS approaches, there are numerous other benefits from computing a large number of re-forecasts. Re-forecasts may facilitate the model development process, for systematic errors that may not be apparent when model changes

are tested on just a few cases may be more obvious with the larger sample afforded by re-forecasts. Extreme weather events are of course more numerous in longer training data sets, so forecast characteristics during these important events can be determined. CDC is making the current re-forecast data set freely available for download at <http://www.cdc.noaa.gov/reforecast> . This data set may be useful for exploring other MOS approaches, for predictability research, and a host of other applications.

In summary, we have showed that MOS approaches can result in dramatic improvements to 6-10 day and week 2 forecasts. Such approaches require a large data set of retrospective forecasts and observations. Given the substantial value added, weather forecast services may wish to evaluate how they can incorporate these statistical techniques into their forecast process.

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## FIGURE CAPTIONS

Figure 1. Locations at which statistical forecast algorithms were evaluated in the conterminous U.S.. Filled circles indicate subset of 153 stations where comparison of re-forecast and CPC are performed for 100 days during the 2001 and 2002 winters. The union of filled and unfilled circles are the stations where re-forecast MOS algorithm is evaluated from 1979 to 2001.

Figure 2. Rank correlation between spread and ensemble mean error using DJF samples from 1979 to 2003.

Figure 3. Illustration of logistic regression method. Ensemble mean week 2 forecast anomaly and corresponding week 2 observed anomaly are plotted for 16 December at a grid point along the Oregon coast. Upper and lower terciles are denoted by dashed lines. Red dots are samples with observed anomalies above the upper tercile; blue dots below. Vertical lines denote bin thresholds for setting tercile probabilities based on the relative frequencies of observed values above the upper tercile. Thick horizontal lines denote the probabilities associated with each bin (refer to probabilities labeled on the right side of the plot). Dotted curve denotes the upper tercile probabilities determined by logistic regression.

Figure 4. Illustration of logistic regression process for week 2 precipitation. Data is for 16 December at grid point near Oregon. (a) Scatterplot of ensemble mean forecast precipitation amount vs. observed amount (determined from an average of all observations inside the  $2.5^\circ \times 2.5^\circ$  grid box). Horizontal dashed lines denote lower and upper terciles. (b) As in (a), but after power transformation. Additionally, vertical black lines denote bin thresholds as in Fig. 3, and thick horizontal solid black lines denote estimated probabilities determined by relative frequency. Dotted curve denotes the upper tercile probabilities determined by logistic regression.

Figure 5. Reliability diagrams week 2 tercile probability forecasts for 850 hPa temperature, DJF forecast data was used from 1979-2001, evaluated over the Northern Hemisphere north of

20° N. Dashed line denotes lower tercile probability forecasts, solid line denotes upper tercile probability reliability. Inset histograms indicate frequency with which extreme tercile probabilities were issued. (a) Probabilities estimated from raw ensemble relative frequency, (b) as in (a), with model bias removed before computation of ensemble frequency, (c) expected RPSS as a function of the correlation between the ensemble mean forecast and verification (see text for details), (d) probabilities estimated from CDC re-forecast MOS.

Figure 6. As in Fig. 5b, but for CDC 6-10 day re-forecast based MOS tercile probability forecasts of (a) surface temperature, and (b) precipitation, evaluated at 355 stations in the U.S. and Guam.

Figure 7. As in Fig. 6, but for week 2 MOS forecasts.

Figure 8. 6-10 day MOS forecast RPSS as a function of station location. (a) Surface temperature, (b) precipitation.

Figure 9. As in Fig. 8, but for week 2 forecasts.

Figure 10. As in Fig. 6, but for CDC 6-10 day MOS forecasts validated during winters of 2001-2002.

Figure 11. As in Fig. 10, but for NCEP/CPC operational 6-10 day forecasts.

Figure 12. As in Fig. 10, but for CDC week 2 MOS forecasts.

Figure 13. As in Fig. 10, but for NCEP/CPC operational week 2 forecasts.

Figure 14. RPSS as a function of the number of years of training data used.

Figure 15. RPSS when 4 years of training data were used, with 1, 2, 3, 4, and 5 days between successive samples in the training data set. The lines labeled “Full 22” indicate the skill (taken from Figs. 6-7) when the full 22 years of cross-validated training data were used.

## Station Locations in CONUS

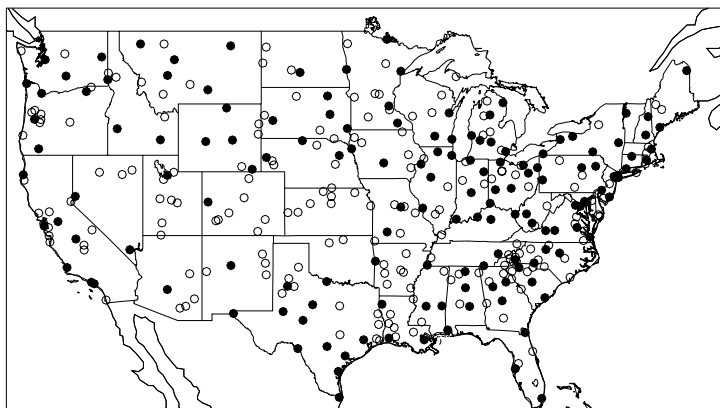


Figure 1. Locations at which statistical forecast algorithms were evaluated in the conterminous U.S.. Filled circles indicate subset of 153 stations where comparison of re-forecast and CPC are performed for 100 days during the 2001 and 2002 winters. The union of filled and unfilled circles are the stations where re-forecast MOS algorithm is evaluated from 1979 to 2001.

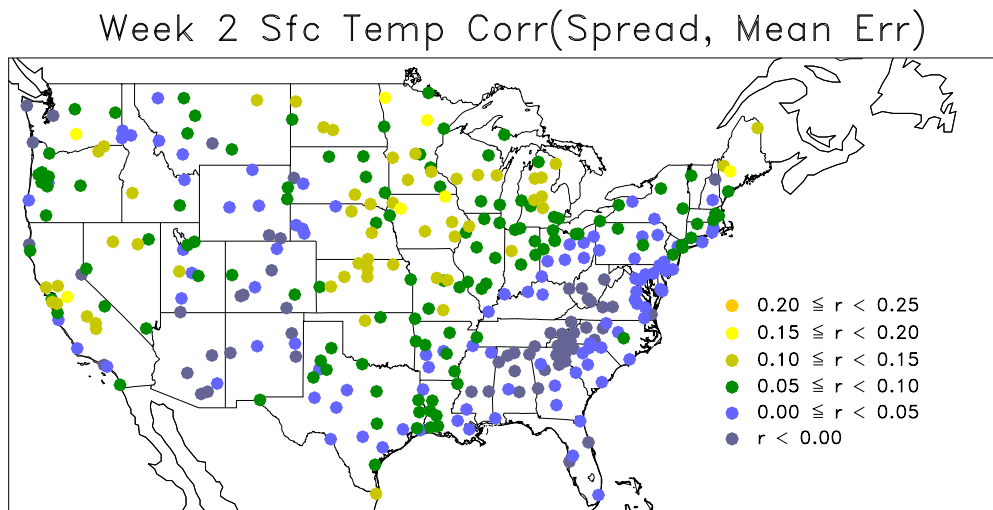


Figure 2. Rank correlation between spread and ensemble mean error using DJF samples from 1979 to 2003.

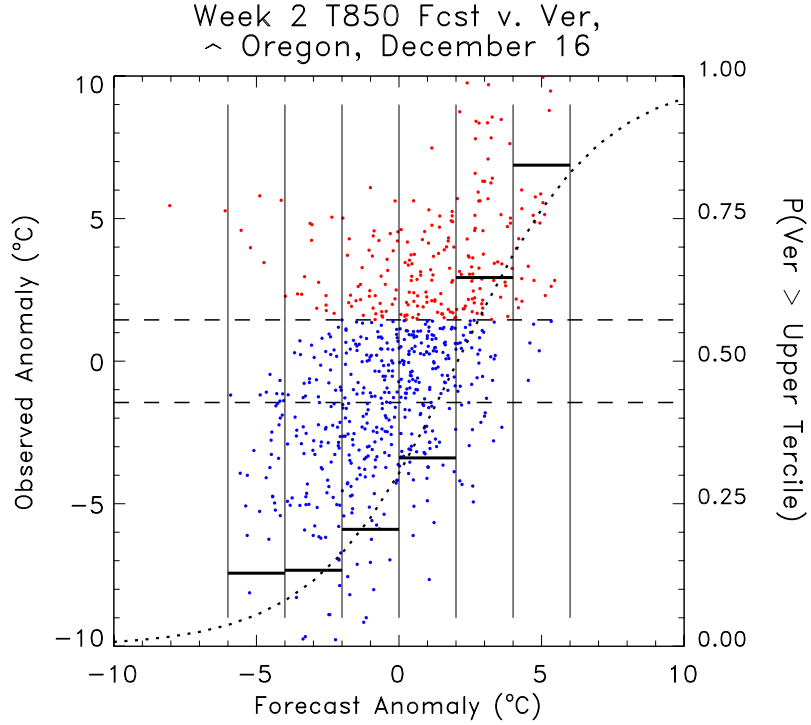


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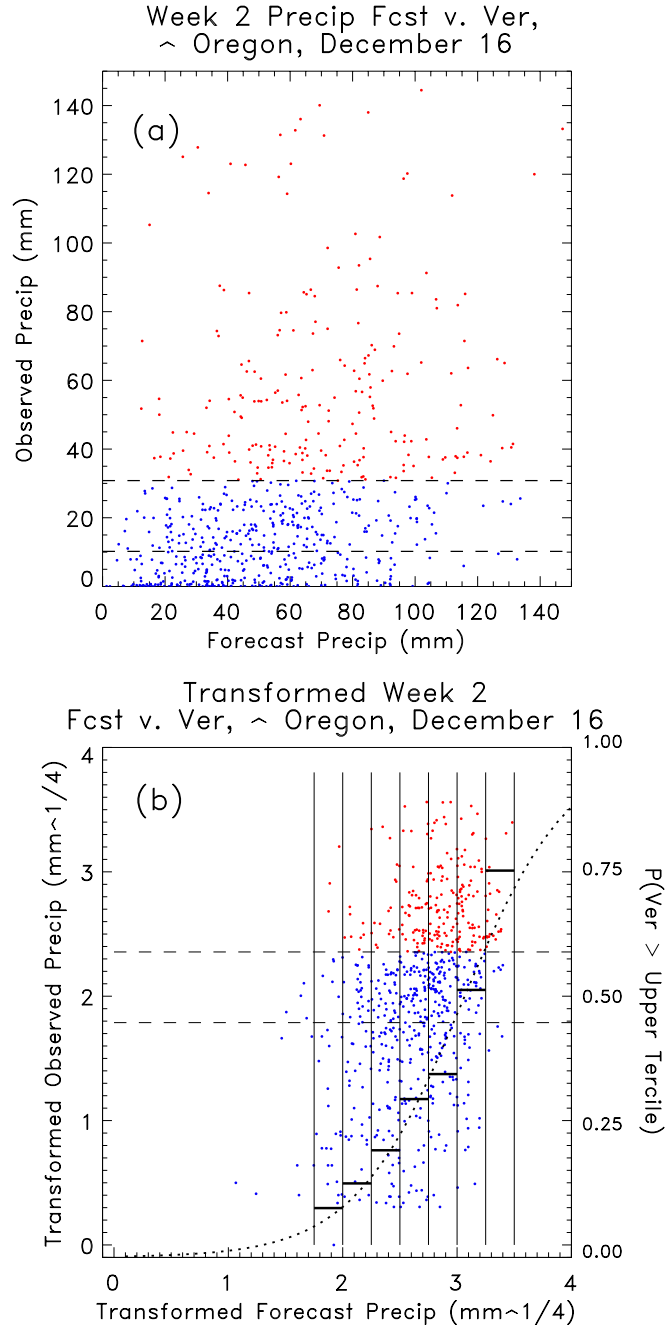


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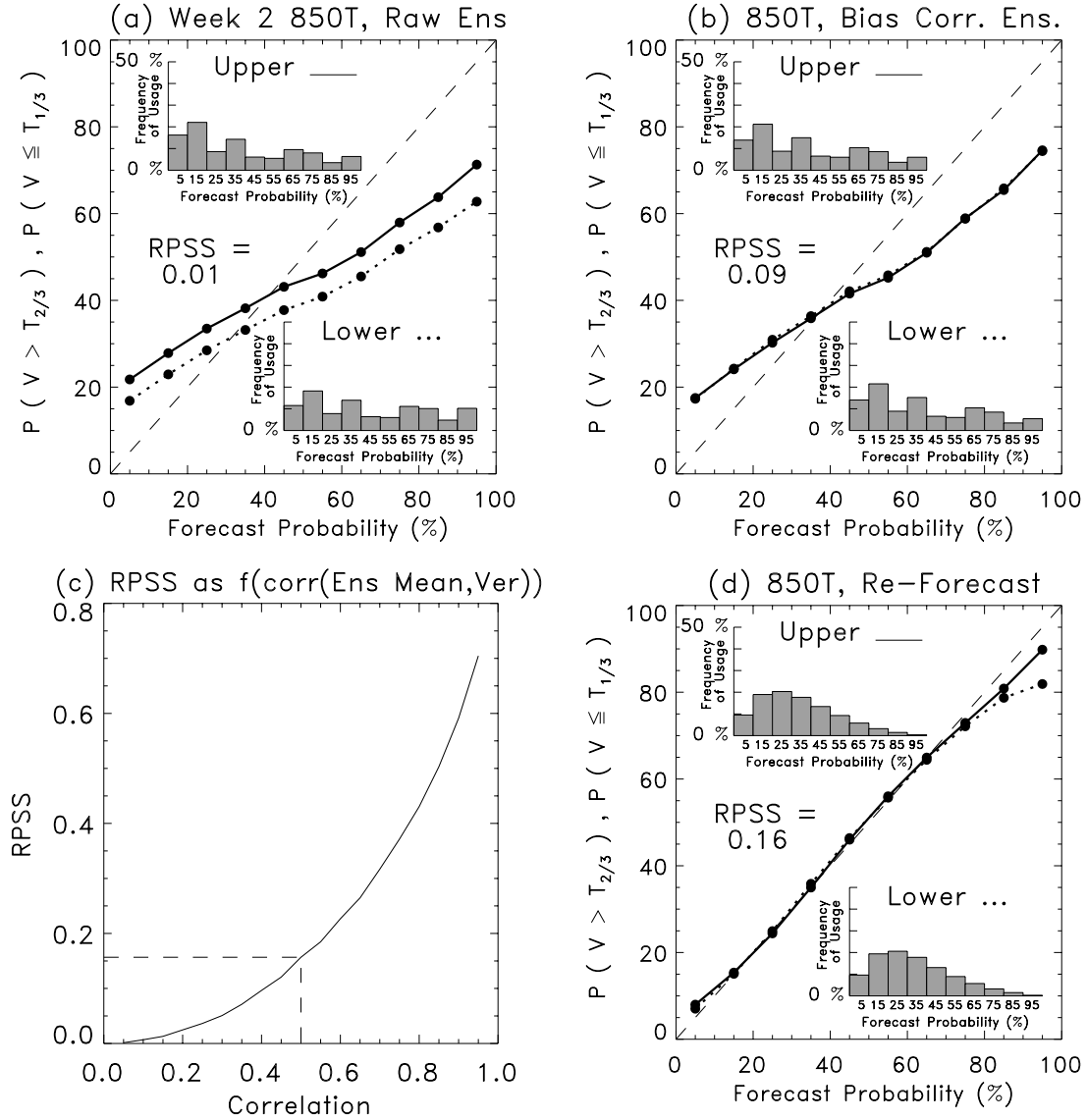


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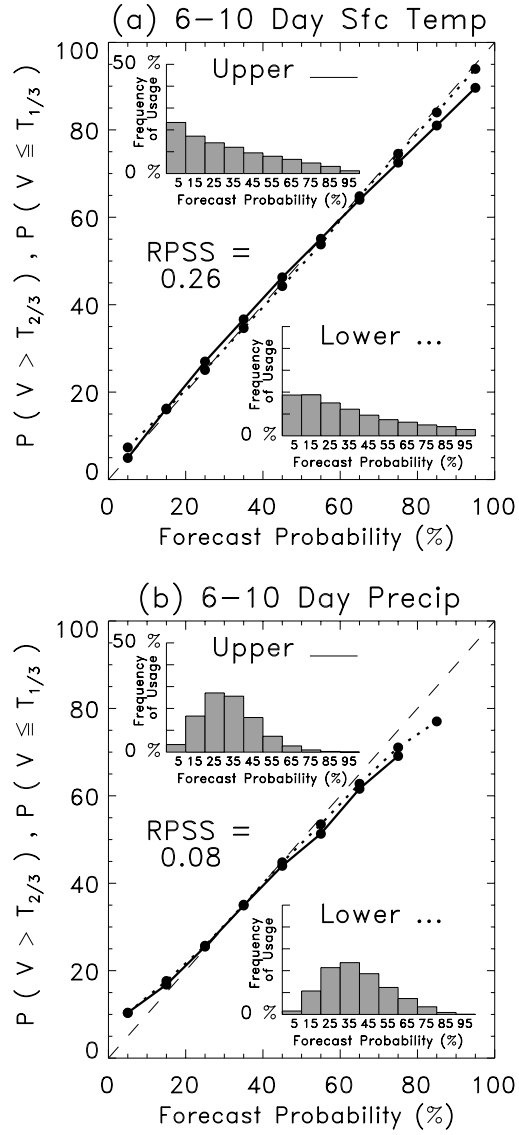


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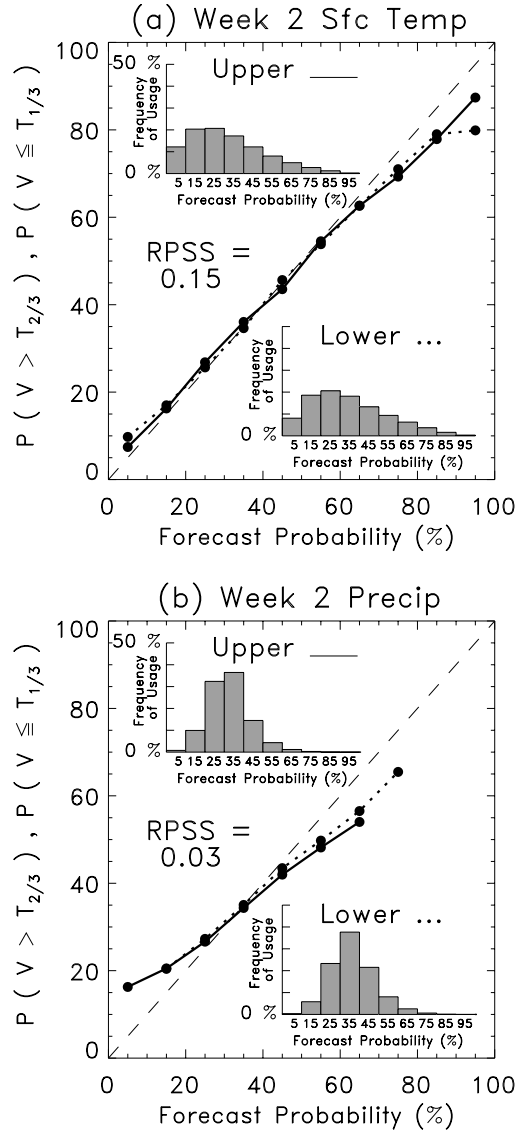


Figure 7. As in Fig. 6, but for week 2 MOS forecasts.

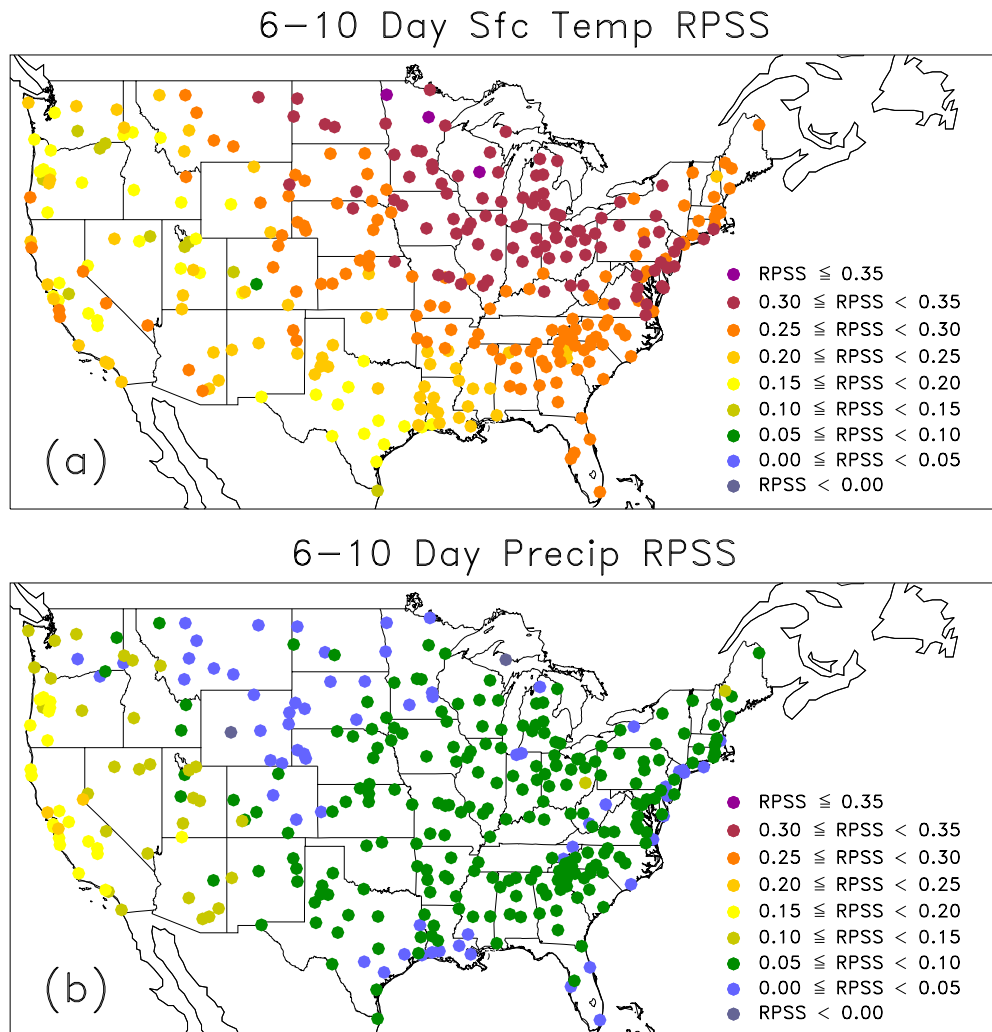


Figure 8. 6-10 day MOS forecast RPSS as a function of station location. (a) Surface temperature, (b) precipitation.

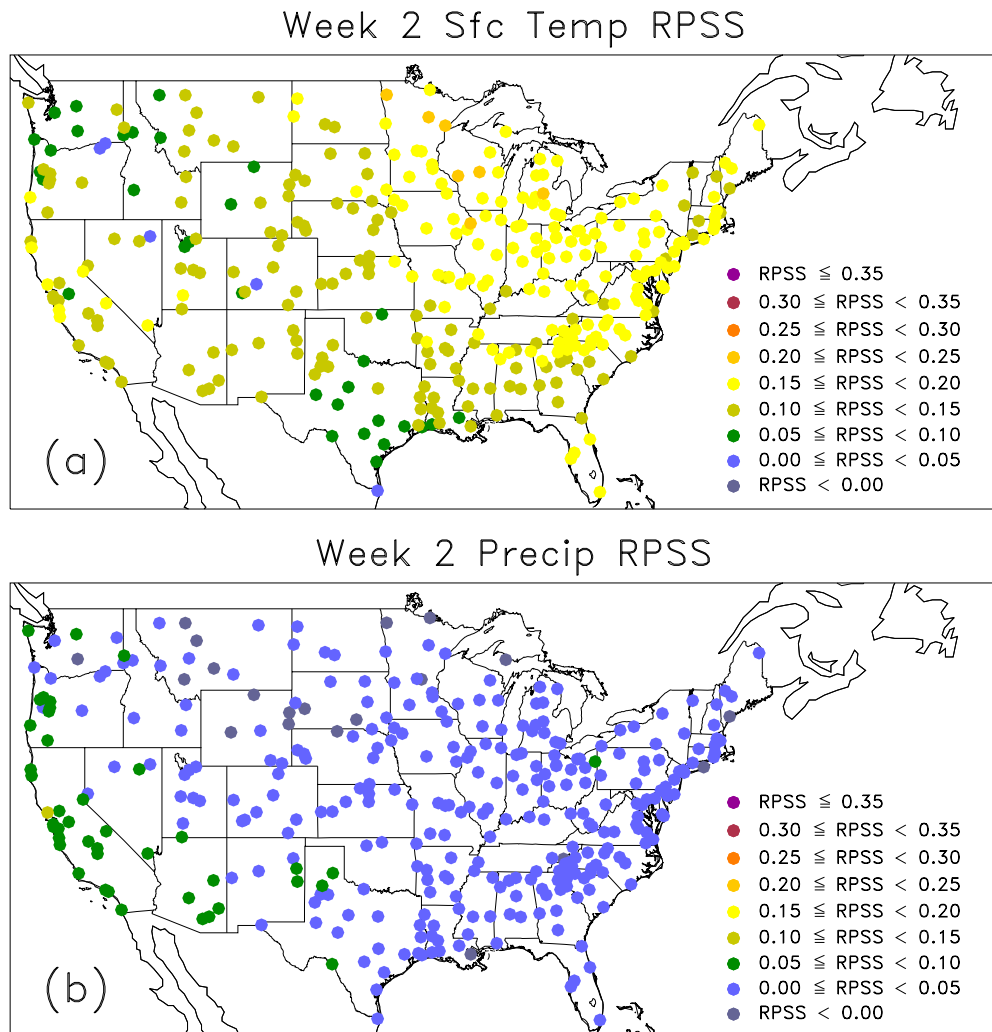


Figure 9. As in Fig. 8, but for week 2 forecasts.

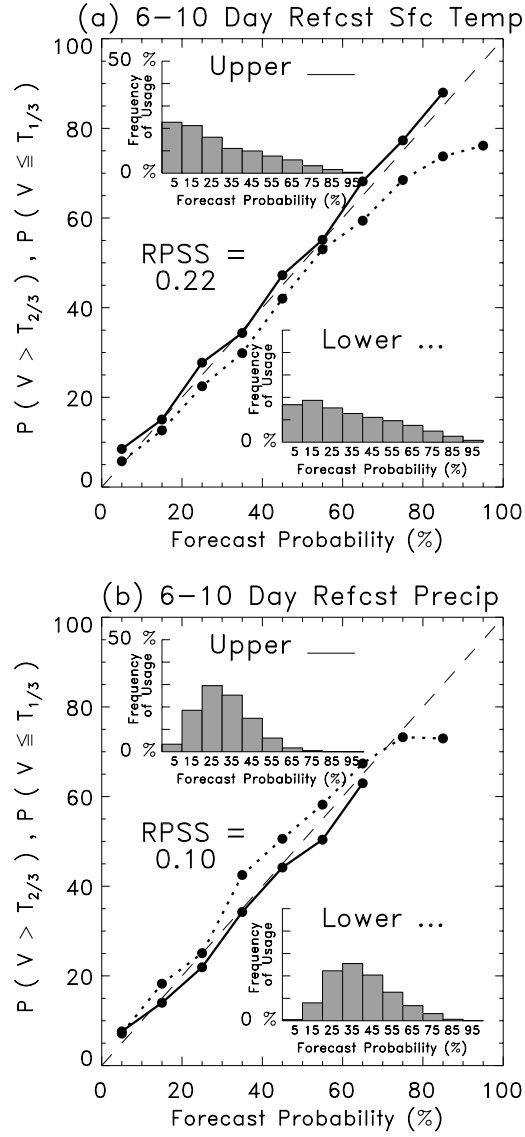


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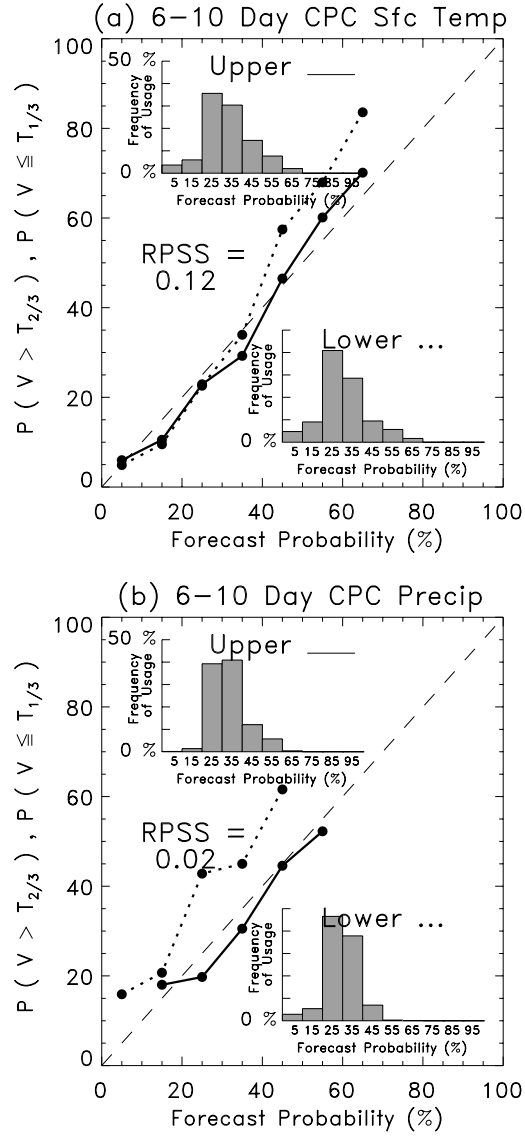


Figure 11. As in Fig. 10, but for NCEP/CPC operational 6-10 day forecasts.



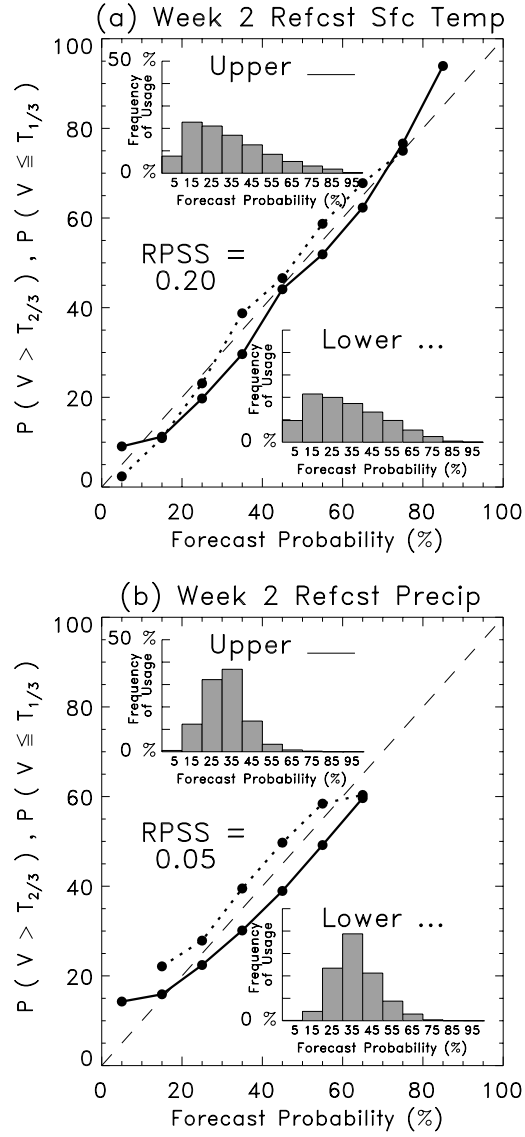


Figure 12. As in Fig. 10, but for CDC week 2 MOS forecasts.

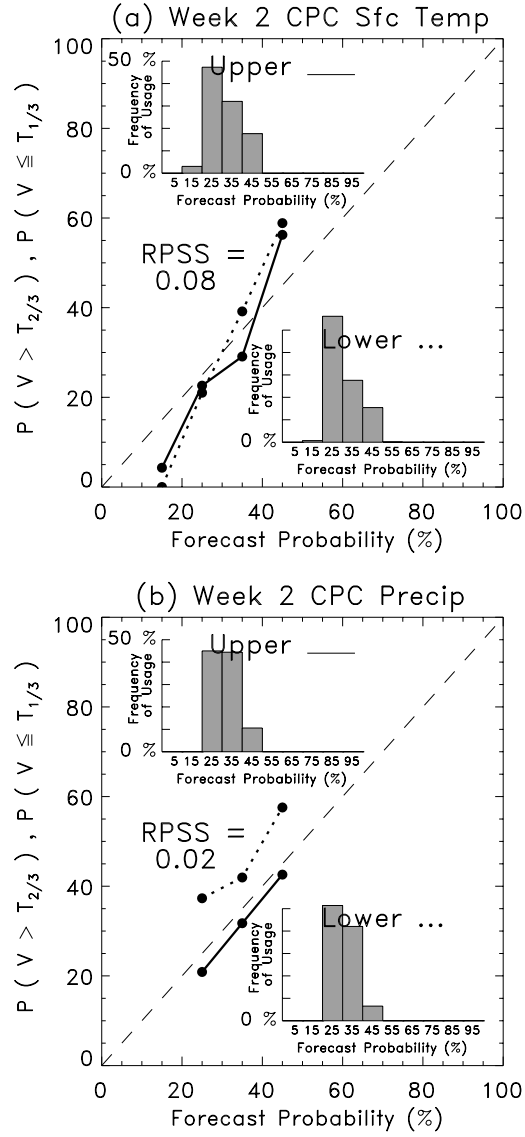


Figure 13. As in Fig. 10, but for NCEP/CPC operational week 2 forecasts.

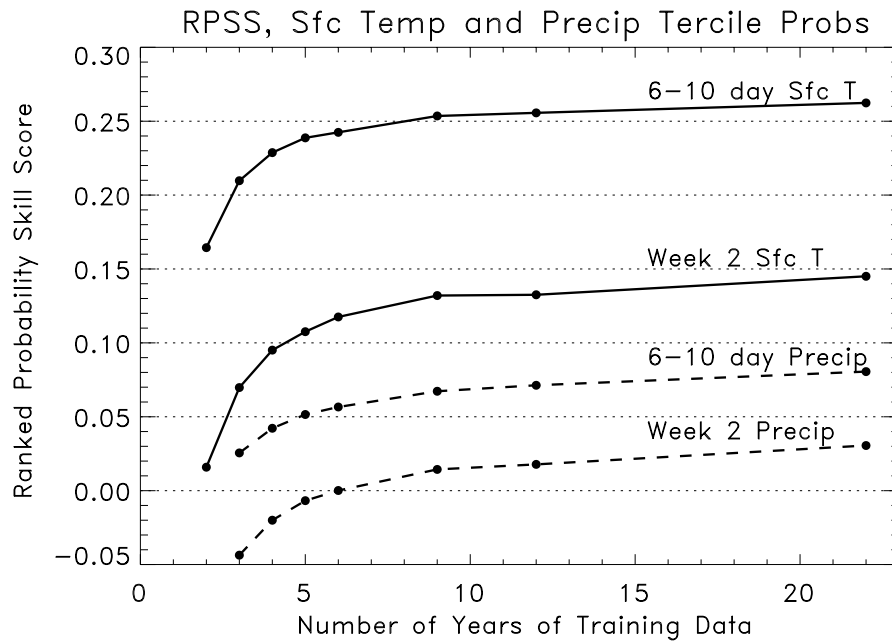


Figure 14. RPSS as a function of the number of years of training data used.

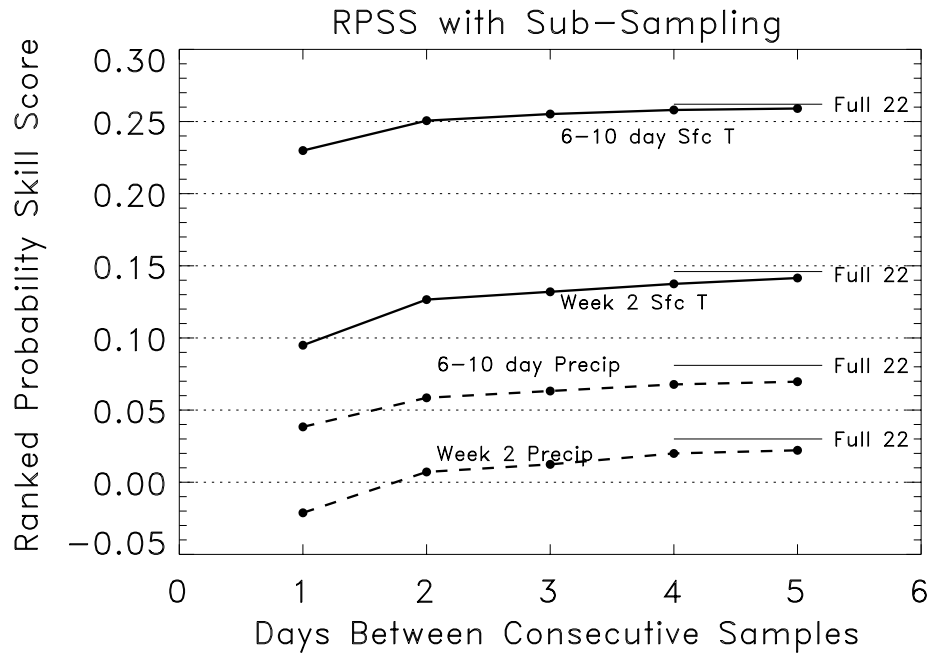


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